Mechanisms of Photo Double Ionization of Helium by 530 eV Photons

A. Knapp[1], A. Kheifets[2], I. Bray[3], Th. Weber[1], A. L. Landers[4], S. Schössler[1], T. Jahnke[1], J. Nickles[1], S. Kammer[1], O. Jagutzki[1], L. Ph. Schmidt[1], T. Osipov[5], J. Rösch[1,6], M. H. Prior[6], H. Schmidt-Böcking[1], C. L. Cocke[5] and R. Dörner[1]

[1] Institut für Kernphysik, Universität Frankfurt, August-Euler-Str. 6, D-60486 Frankfurt, Germany
[2] Research School of Physical Sciences and Engineering, Australian National University Canberra ACT 0200, Australia
[3]Centre for Atomic, Molecular and Surface Physics, Murdoch University, Perth, 6150 Australia
[4] Dept. of Physics, Western Michigan Univ., Kalamazoo, MI 49008
[5] Dept. of Physics, Kansas State Univ., Cardwell Hall, Manhattan KS 66506
[6] Lawrence Berkeley National Lab., Berkeley CA 94720

How does a single photon couple to two electrons in an atom? This question has been extensively discussed in the literature. Most of this discussion has been focused on the photo double ionization (PDI) of the helium atom which is the simplest two-electron-single-photon process. It is generally believed that at high photon energies the shake-off mechanism makes the largest contribution to PDI. The shake-off is a relaxation of the correlated initial state onto the new He^+ eigenstates after a sudden removal of one atomic electron. In contrast, close to the threshold, mainly one electron absorbs the photon and knocks out the second electron in an (e,2e) like collision (the process which is called in the literature the two-step-one, or TS1). The whole discussion on the PDI mechanisms is based solely on theory and on measured total cross sections. Differential data were available only in the regime of low energies, where the long range interaction between the electrons completely masks the signatures of the ionization mechanisms.

In this joint experimental and theoretical work we provide the first direct evidence for both mechanism by measuring the angular distributions of the photoelectrons by use of the COLTRIMS technique (Cold Target Recoil Ion Momentum Spectroscopy). The experiments have been performed at Bl. 4. They cover double ionization by linear and circular polarized light.

The following observations present the arguments for a two-step picture in which one electron absorbs the photon energy and its angular momentum and, subsequently, the second electron is either shaken-off or knocked out. The top panel of 1 shows the measured and calculated SDCS. It has a characteristic U-shape and peaks sharply at 0 eV

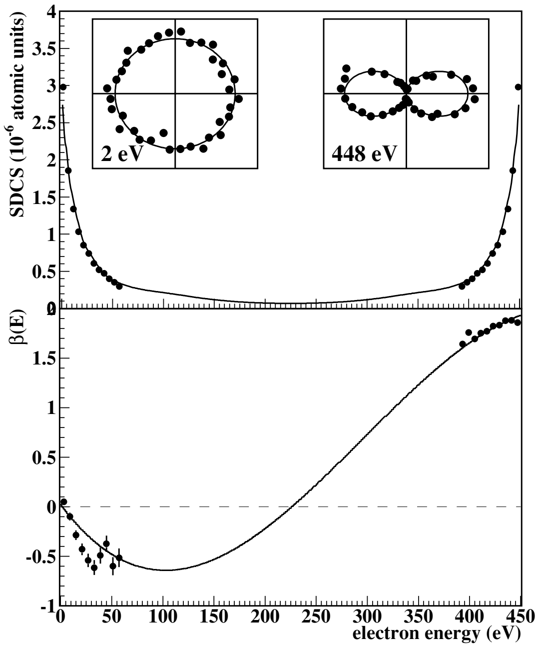

Figure 1: PDI of He at $\hbar\omega = 529$ eV. a) SDCS $d\sigma/dE$. The line is a CCC calculation. The insets show the DDCS $d\sigma^2/(d\Omega dE)$ at $E = 2$ eV and 448 eV. b) The asymmetry parameter β versus the electron energy.

and 450 eV. This run of the curve is in contrast to the SDCS close to the threshold which is almost flat. The bottom panel of 1 shows the measured and calculated β parameter. We find an angular asymmetry parameter $\beta \simeq 2$ for the very fast electrons and $\beta \simeq 0$ for the very slow electrons. Two examples of the experimental DDCS at $E = 2$ eV and 448 eV are shown in the insets together with the line obtained from CCC estimates of the SDCS and β. A very asymmetric energy sharing together with an angular asymmetry parameter $\beta \simeq 2$ for the fast electron indicate that the fast electron absorbs not only most of the photon energy but also its angular momentum. This directly suggests an interpretation of the PDI as a two-step process with the fast electron being the primary photoelectron. The very slow electrons are emitted isotropically at very low energies as expected for the shake-off, while β becomes slightly negative for higher energies indicating a major role of the TS1 at higher energies of the slower electron.

After establishing the validity of a two step picture we show now, that the second step of the PDI is dominated by the shake-off mechanism for very low energetic electrons (about 1 eV), while 30 eV electrons are created mainly by a binary (e,2e) like collision. In brief, the shake-off results in a almost isotropic, slightly backward directed emission of the slow electron with respect to the fast one, while any binary collision between the electrons leads to an angle of 90 deg between them.

The TDCS for electrons $E_2 < 3$ eV (figure 2b) has a pear-like shape peaked at 180° to the fast electron. Contrary to all TDCS reported at lower photon energies so far, these slow electrons show a significant intensity for parallel emission into the same direction. This is possible because of the very asymmetric energy sharing of the two electrons. The

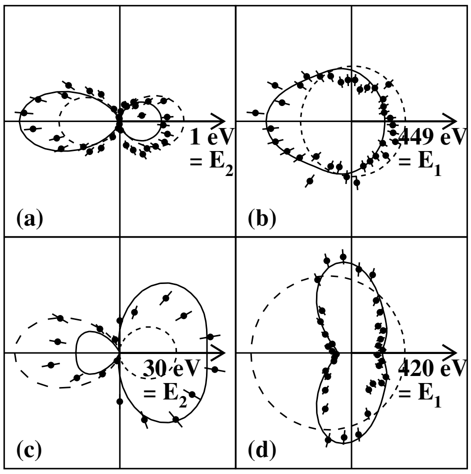

Figure 2: TDCS of the He PDI at 529 eV photon energy. In all panels the electrons are coplanar within $\pm 25°$, the polarization axis is horizontal. The direction and the energy of one of the two electrons is fixed as indicated by the number and the arrow, i.e. the slow electron is fixed in panels (a) and (c) and the fast electron is fixed in (b) and (d). The polar plots show the angular distribution of the complementary electron. The upper panels (a) and (b) are for the case $E_2 \simeq$ 2 eV; the lower panels have $E_2 \simeq$ 30 eV. The solid line is a full CCC calculation, the dashed line is a shake-off only CCC calculation. The measurements are normalized to the full CCC calculation.

solid line is a full CCC calculation which is in excellent agreement with the measurements.

The TDCS for electrons $E_2 \simeq 30$ eV (figure 2 c,d) are completely different from the low energy ones. We find emission of the electron into a narrow cone at 90° to the fast electron (figure 2 d). An angle of 90° between the electrons is expected from a binary collision between the electrons.

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Principal investigator: Reinhard Dörner, Institut fuer Kernpyhsik, August Euler Str. 6, D-60486 Frankfurt, Germany, email: doerner@hsb.uni-frankfurt.de, phone: 049 69 798 24218